Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 2 (2016) 1635–1642

Structural Integrity Procedia

www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

WES 2808 for Brittle Fracture Assessment of Steel Components under Seismic Conditions – Part V: Equivalent CTOD ratio for correction of constraint loss in beam-to-column connections

Mitsuru Ohata[a]*, Yasuhito Takashima[b], Fumiyoshi Minami[b]

[a]*Materials and Manufacturing Science, Osaka University, 2-1, Yamadaoka, Suita, Osaka 565-0871, Japan*
[b]*Joining and Welding Reseach Institute, Osaka University, 11-1, Mihogaoka, Ibaraki, Osaka 567-0047, Japan*

Abstract

Crack-tip plastic constraint in beam-to-column connections with a surface crack 1) at the bottom of a conventional type of weld access hole and 2) at weld start/end points of butt welds to connect beam flange and diaphragm subjected to bending moment were analyzed by FEM. The equivalent CTOD ratio β used for engineering toughness correction for constraint loss for the beam-to-column connections are compared with those for the wide plate components with the same size of a crack subjected to tension load. Then, the analyses of β by means of the wide plate component, CSCP and ESCP, are conducted, and the crack depth effect on β is formulated with focusing on crack depth ratio *a/t*.

Keywords: beam-to-column connection; bending load; toughness correction; constraint loss; Weibull stress; equivalent CTOD ratio

1. Introduction

Large plastic deformation due to earthquake sometimes induces brittle fracture with cleavage mode in steel frame structures. Stress/strain concentrators in beam-to-column connection can be an origin of such brittle fracture as reported by Toyoda (1995); where a ductile crack propagated duo to cyclic loading from a crack-like welding defect in start and end points of butt welds to connect beam flange to column or a toe of scallop (bottom of weld access

* Corresponding author. Tel.: +81-6-6879-7545; fax: +81-6-6879-7545.
E-mail address: ohata@mapse.eng.osaka-u.ac.jp

Copyright © 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer review under responsibility of the Scientific Committee of ECF21.
10.1016/j.prostr.2016.06.207

hole) at beam end can be a trigger. One of the issues for the safety assessment against brittle fracture from such cracks in steel frame components under seismic loading is to address the plastic constraint. Even though the beam-to-column connections are subjected to bending moment under seismic loading, the crack existed in the beam flange are mainly subjected to tension load. Therefore, the crack-tip plastic constraint for such components is expected to be much lower than that for the standard fracture toughness specimen subjected to pure bending load.

In this study, crack-tip plastic constraint in beam-to-column connections subjected to bending moment was analyzed by FEM in typical cases of crack size and mechanical properties. In order to address the constraint loss, the equivalent CTOD ratio as engineering definition for CTOD correction, which was proposed by Ohata and Minami (2012) based on the Beremin model (1983), was estimated and compared with those for wide plate components under tension load. Then, the equivalent CTOD ratios of the components were systematically analyzed and formulated for the various cases of crack size and specimen thickness.

2. Analysis of crack-tip plastic constraint for beam-to-column connection under bending load

2.1. Models and method for analysis

The target steel frame structure used in this analysis is one of the typical beam-to-column connection in buildings in Japan, where the box-shaped column that has cold formed rectangular hollow section are connected with the H-section beam through the diaphragm, as shown in Fig. 1. The thickness of the beam flange is 25 mm. Two types of detail of connection with a crack were modeled. One is the component with a surface crack at the bottom of a conventional type of weld access hole (BC-model 1), which assumes fracture from the propagated ductile crack at the scallop toe. This type of weld access hole is based on JASS6 of the Architectural Institute of Japan. The other is the component with a surface crack at weld start and end points of butt welds to connect beam flange and diaphragm (BC-model 2), which assumes fracture from a crack-like defect such as lack of fusion. In this model, curvature is applied to the bottom of the weld access hole to avoid the ductile cracking associated with strain concentration. These models were subjected to bending load at the end of beam.

In order to discuss the loading mode effect on crack-tip plastic constraint, center surface crack panel (CSCP) and edge surface crack panel (ESCP) of thickness B = 25 mm subjected to tension load were modeled, as shown in Fig. 1. In the case of weld start/end crack, effect of geometrical discontinuity was additionally discussed by means of ESCP-GD model subjected to tension load. 3-point bend specimen (3PB) of thickness B = 25 mm as standard fracture toughens specimen with a deep crack of a_0/W=0.5 (a_0: crack depth, W: specimen width) was also modeled.

The steel supposed in this analysis has yield-to-tensile ratio R_Y = 0.6 (=σ_Y/σ_T ; σ_Y: yield strength = 427 MPa, σ_T: tensile strength = 711 MPa). The low R_Y-value is selected in consideration of the Baushinger effect of steel after large-scale cyclic loading at the earthquake. The material followed the power-hardening law of Swift type $\bar{\sigma} = C(1 + \bar{\varepsilon}_p / \alpha)^n$, where $\bar{\sigma}$ and $\bar{\varepsilon}_p$ are the equivalent stress (Mises stress) and equivalent plastic strain, respectively, C is the elastic limit, n and α are material constants (n being a strain hardening coefficient).

The FE-analysis was conducted with the FE-code, ABAQUS ver. 6.11. The specimens were modeled with 8-node isoparametric elements with 8-Gaussian points. The minimum element size at the crack tip in 2-dimensional plane perpendicular to the crack was 0.03 x 0.03 mm, which was common to the all specimens. The CTODs of the surface cracked components were defined at the deepest point of the crack by a tangential method (Harrison (1980)). The CTODs of the fracture toughness specimen was calculated in accordance with well-defined toughness testing standards ISO 12135 (2002).

2.2. Equivalent CTOD ratio for assessing constraint loss

The Weibull stress σ_W, which was originally proposed by Beremin (1983) as a fracture driving force for cleavage fracture of ferritic steels, was used for analyzing CTOD correction for constraint loss in structural components. The Weibull stress σ_W is defined as

$$\sigma_W = \left[\frac{1}{V_0} \int_{V_f} (\sigma_{eff})^m dV \right]^{1/m} \tag{1}$$

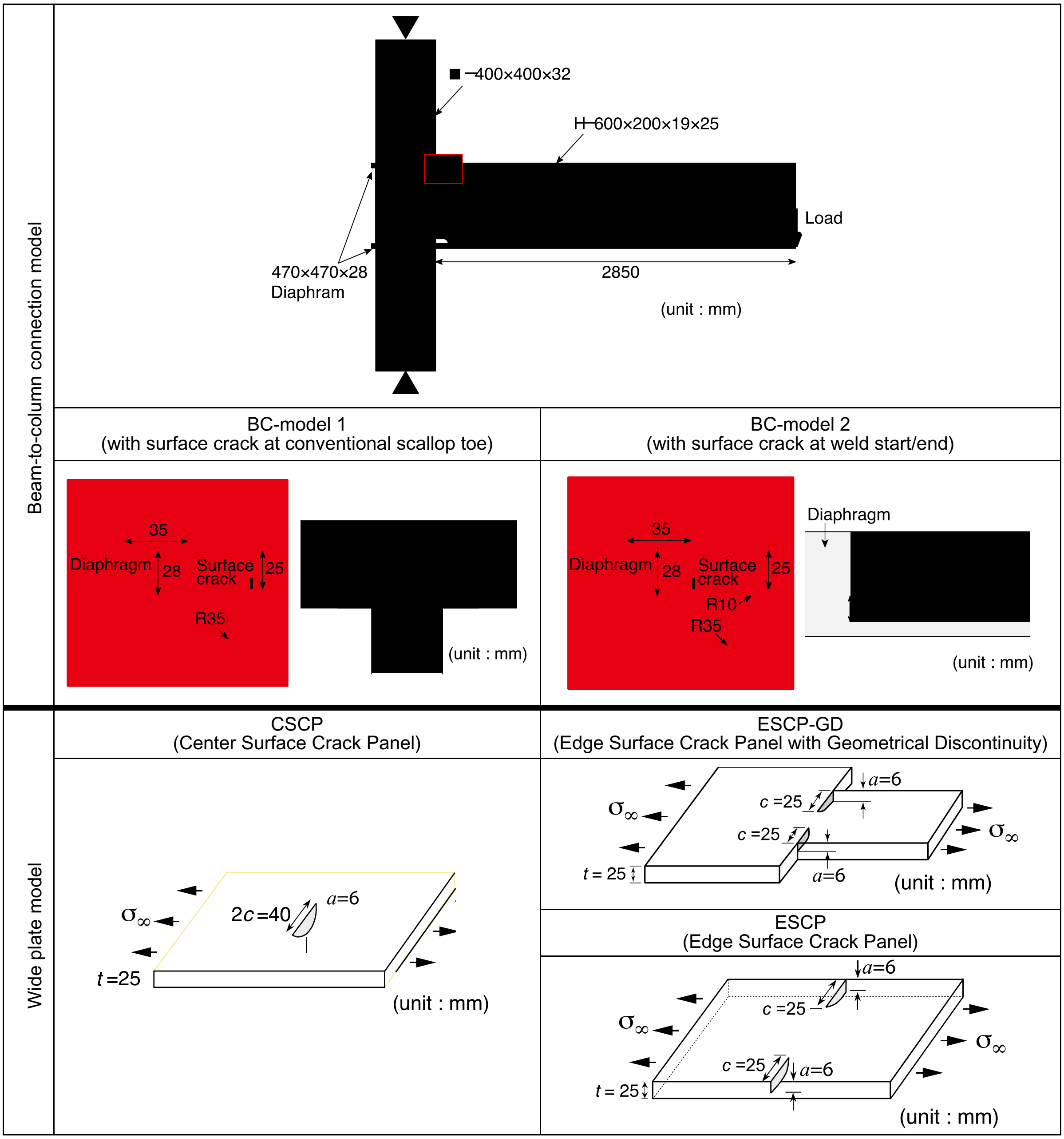


Fig. 1 Beam-to-column connections and wide plates with surface crack used for FE-analysis.

where V_0 and m are a reference volume and a material parameter, respectively, V_f almost corresponds to the plastic zone near the crack tip, and σ_{eff} is an effective stress for cleavage fracture proposed by Minami and Ruggierri et al (1992). Based on the Weibull stress criterion, the equivalent CTOD ratio β for constraint loss correction was defined as $\beta = \delta / \delta_{struc}$ as shown in Fig. 2, where δ and δ_{struc} are CTODs of a standard fracture toughness specimen and a structural component at the same level of the Weibull stress. The β generally depends on the load level (CTOD level), and decreases with increasing CTOD δ in standard fracture toughness specimen. However, in most cases, clear inflection can be seen in δ - β relation, and beyond this inflection point, the CTOD level has only a slight effect on β (Minami et al (2006), Ohata et al (2012)). The CTOD $\delta_{SSY\ limit}$ under plane strain condition defining the small-scale yielding (SSY) limit of the 25mm thick fracture toughness specimen is larger than 0.01mm that is almost corresponds to the inflection point. From an engineering point of view, the β where the CTOD of standard fracture toughness specimen is 0.01mm was adopted for a measure of CTOD toughness correction of structural components. ISO 27306 (2009) employs this engineering definition of β and provides nomographs of β for various types of wide plate components, whereas its application is restricted in the load range beyond the δ_{SSY} limit.

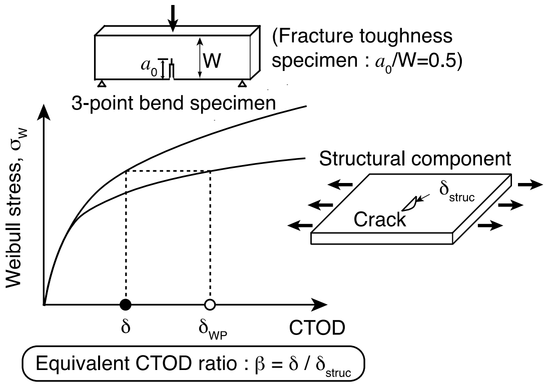


Fig. 2 Equivalent CTOD ratio β for constraint loss correction based on the Weibull stress criterion.

2.3. Equivalent CTOD ratio in beam-to-column connections

Crack-tip constraint for the beam-to-column connection model, BC-model 1, with surface crack at conventional scallop toe was analyzed for the steel with R_Y = 0.60. Figure 3 compares Weibull stress with m = 20 for the BC-model 1 subjected to bending and tension load and CSCP subjected to tension load. As far as tension loading is applied, BC-model 1 provides the same Weibull stress as that for CSCP despite the existence of access hole to induce stress/strain concentration. Moreover, it was interesting that the bending load to the BC-model 1 was found not to significantly increase Weibull stress. Of course, these structural components provided the larger Weibull stress than the 3PB specimen.

From these Weibull stress calculations, the engineering equivalent CTOD ratio β (= δ / δ_{struc}) at δ = 0.01mm for 3PB specimen was estimated. As shown in Fig. 4, the β for the BC-model 1 under bending load was almost the same as that for BC-model 1 as well as CSCP under tension load irrespective of the m-value.

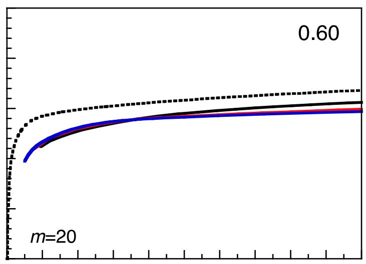


Fig. 3 Effect of loading mode (bending or tension) on Weibull stress in BC-model 1, and comparison with that for CSCP under tension load.

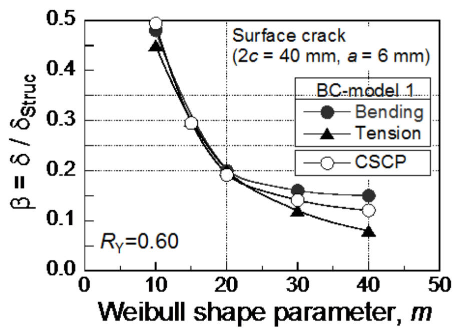


Fig. 4 Comparison between engineering equivalent CTOD ratios for BC-model 1 under bending and tension load and CSCP under tension load.

For the case of the BC-model 2, where fracture could occur from weld start and end points of butt welds to connect beam flange and diaphragm rather than the scallop toe, crack-tip constraint was analyzed for also the steel with R_Y = 0.60. The effect of loading mode, that is bending or tension, on crack-tip constraint was discussed by comparing Weibull stress for the BC-model 2 subjected to bending load and for the ESCP with geometrical discontinuity subjected to tension load (ESCP-GD). As shown in Fig. 5, no effect of loading mode was observed on Weibull stress in the wide range of CTOD. This result implies that the bending load does not influence crack-tip constraint for an edge surface crack at beam flange. It can be also interpreted by comparing Weibull stress for ESCP-GD and ESCP under tension load that the geometrical discontinuity around crack-tip can induce stress/strain concentration but not affect the crack-tip constraint. And in any case, the 3PB specimen provided much larger Weibull stress as shown in Fig. 5.

Engineering equivalent CTOD ratio β (= δ / δ_{struc}) for these structural components was estimated and summarized in Fig. 6 as a function of m-value. The β for the BC-model 2 under bending load and for the ESCP-GD under tension load were almost the same irrespective of the m-value, whereas these β showed slightly lower value compared to that for ESCP under tension load especially at the lower m-value. A slight gradient of global tension stress in thickness direction of a flange seemed to be a reason to slightly reduce the crack-tip constraint.

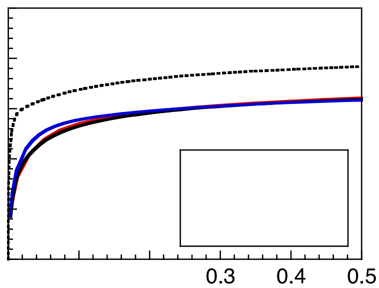


Fig. 5 Comparison between Weibull stress for BC-model 2 under bending load and ESCP with/without geometrical discontinuity under tension load.

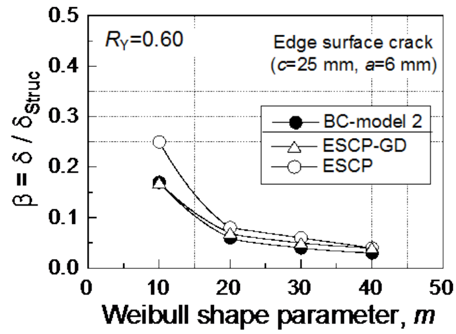


Fig. 6 Comparison between engineering equivalent CTOD ratio for BC-model 2 under bending load and ESCP with/without geometrical discontinuity under tension load.

From these results, the crack-tip constraint expressed by the engineering equivalent CTOD ratio β for the beam-to-column connections subjected to bending load was found to be almost the same as that for the wide plate components with the same size of a crack subjected to tension load.

3. Calculation of constraint loss in structural components

The β for wide plate component under tension load found to be able to use for constraint loss correction for the beam-to-column connection with a crack under seismic loading. Then, crack size effect, especially crack depth effect on the β for constraint loss correction was systematically estimated by means of the wide plate component under tension load.

3.1. Target structural components

Assuming a surface crack at scallop toe and at weld start/end points of butt welds in beam-to-column connection, center surface crack panel (CSCP) and double edge surface crack panel (ESCP) were used for analysis, respectively. Additionally, double edge through-thickness crack panel (ETCP) was modeled assuming a ductile crack growth under cyclic loading. The crack size and the plate thickness covered in this analysis are summarized in Table 1.

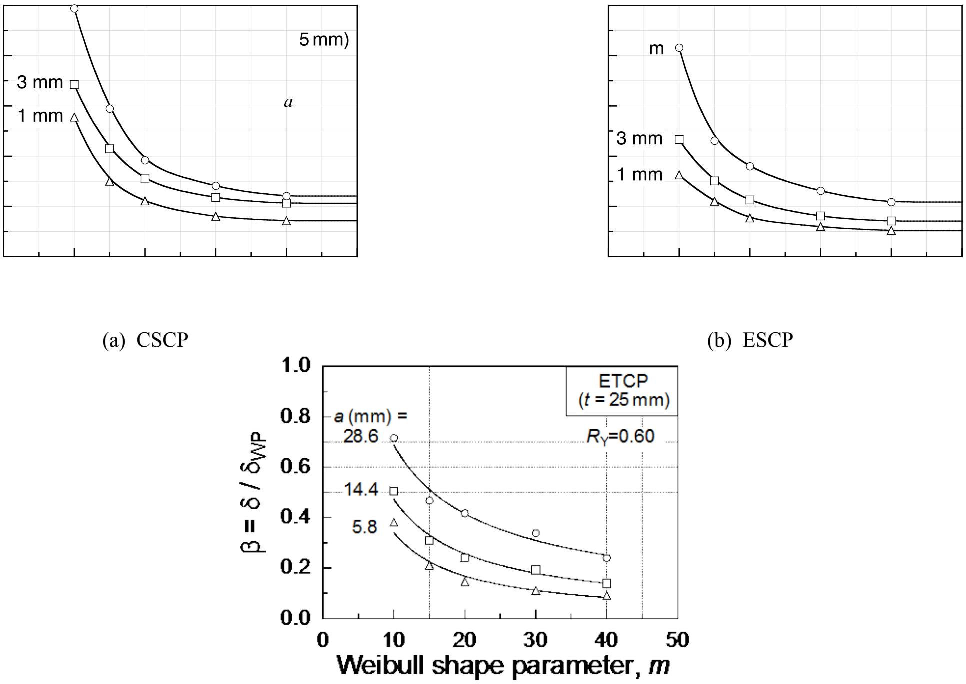
Table 1 Range of crack size and plate thickness.

	Crack length	Crack depth	Crack depth ratio	Plate thickness
CSCP	$2c$ = 40 mm	$1 \leq a \leq 6$ mm	$0.04 \leq a/t \leq 0.24$	$12.5 \leq t \leq 50$ mm
ESCP	$2c$ = 30 mm	$1 \leq a \leq 6$ mm	$0.04 \leq a/t \leq 0.24$	$12.5 \leq t \leq 50$ mm

ETCP	-	$5.8 \le 2a \le 28.6$ mm	-	-

3.2. Effect of crack depth on equivalent CTOD ratio β

The engineering equivalent CTOD ratio β for the wide plates with $R_Y = 0.60$ was analyzed. Figure 7 shows the effect of crack depth a for the CSCP, ESCP and ETCP with plate thickness t = 25mm. In the all wide plates, the strong effect of crack depth on β was presented, and β is decreased with decreasing a and with increasing Weibull shape parameter m-value.



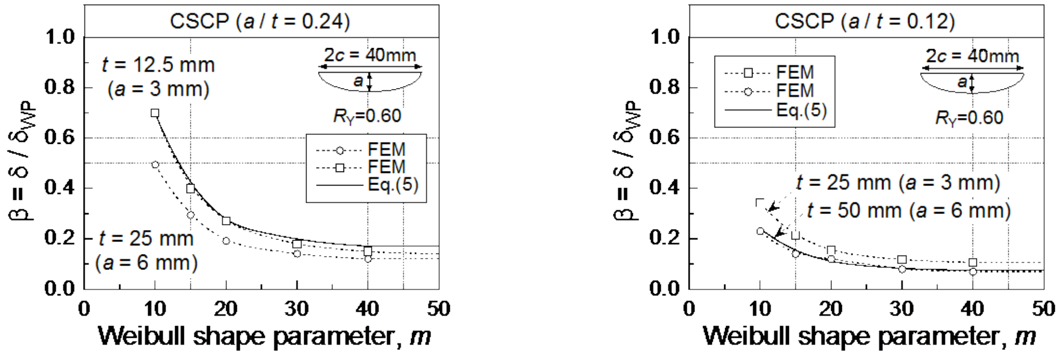
(a) CSCP (b) ESCP

Fig. 7 Effect of crack depth on equivalent CTOD ratio β for wide plates with thickness t = 25 mm.

3.3. Formulation of crack depth effect on equivalent CTOD ratio β for surfacr crack coponent

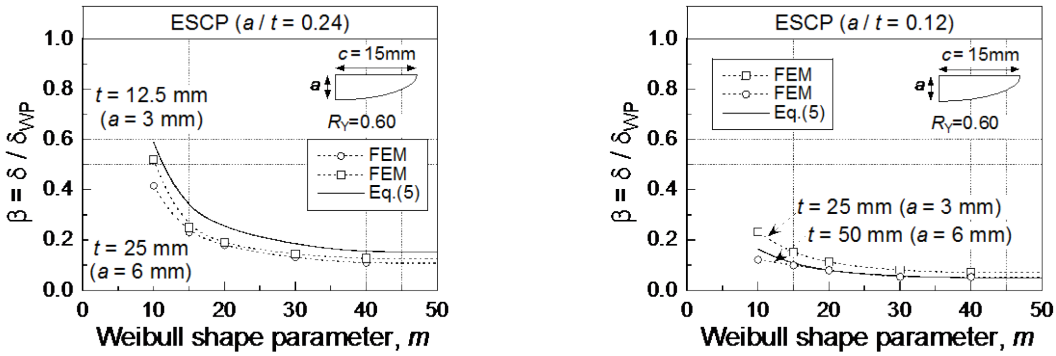
In the practical steel frame structure, thickness of a flange plate ranges from about 10 mm to 50 mm. On the other hand, crack-tip constraint for a surface crack component might be controlled by the relative crack depth to plate thickness, whereas only the crack depth would influence crack-tip constraint irrespective of plate thickness in the case of a through-thickness crack. Then, with focusing on the crack depth ratios a/t for a surface crack component, the crack depth effect on β was tried to generalize.

Figures 8 and 9 present the effect of plate thickness on β under constant crack depth ratios a/t (= 0.24 and 0.12) for CSCP and ESCP, respectively. Thicker plates provided the lower β despite the constant a/t in all cases. In order to elucidate the reason why the plate thickness affected the β even though the a/t was the same, the effect of plate thickness on Weibull stress for the wide plates with a crack of constant a/t and 3PB specimen were discussed. Figure 10 shows one example of the comparison between Weibull stress for CSCP and ESCP with a given crack depth ratio a/t = 0.24 and 3PB specimen, which has different thickness t = 25 mm and 12.5 mm. Weibull stress for wide plate does not depend on the plate thickness t under a/t = 0.24. On the contrary, thicker plate gave larger Weibull stress in the case of 3PB specimen, which came from the simple size effect of the process zone in thickness direction. Namely, it was found that the crack depth effect on β for CSCP and ESCP could be quasi-theoretically formulated as the plate thickness effect under a given crack depth ratio *a/t*.



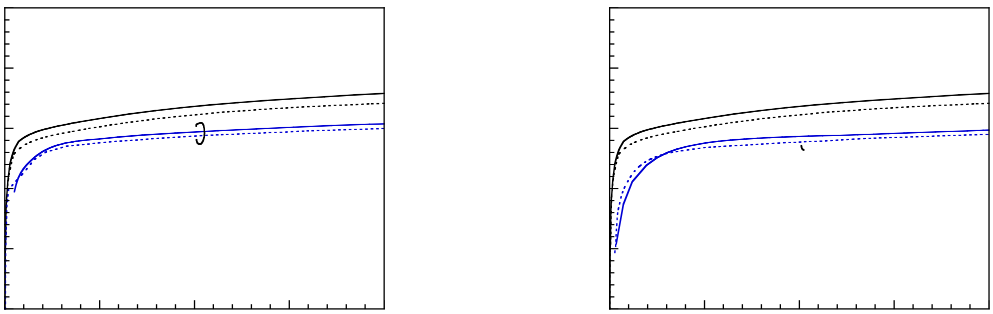
(a) *a*/*t*=0.24 (b) *a*/*t*=0.12

Fig. 8 Effect of crack depth on equivalent CTOD ratio β for CSCP.



(a) *a*/*t*=0.24 (b) *a*/*t*=0.12

Fig. 9 Effect of crack depth on equivalent CTOD ratio β for ESCP.



(a) CSCP (*a*/*t* =0.24) (b) ESCP (*a*/*t* =0.24)

Fig. 10 Plate thickness effect on Weibull stress for 3PB specimen and wide plate

The $\beta(t)$ for the wide plate with thickness t can be approximately correlated with the $\beta(25)$ for the 25 mm thick wide plate as follows;

The ration of $\beta(t)$ to $\beta(25)$ can be defined as Eq. (2),

$$\beta(t)\ :\ \beta(25)=\frac{\delta_{c,3PB}(t)}{\delta_{c,CSCP}(t)}\ :\ \frac{\delta_{c,3PB}(25)}{\delta_{c,CSCP}(25)} \tag{2}$$

where $\delta_{c,3PB}(t)$ and $\delta_{c,3PB}(25)$ are critical CTOD for 3PB specimens with thickness t and 25 mm, respectively, and $\delta_{c,WP}(t)$ and $\delta_{c,WP}(25)$ are critical CTOD for wide plates with thickness t and 25 mm, respectively. Here, $\delta_{c,WP}(t)$ and $\delta_{c,WP}(25)$ can be the same, because the Weibull stress for both wide plates are consistent with other as long as the a/t is constant. Therefore, the Eq.(2) becomes simply Eq.(3).

$$\beta(t)\ :\ \beta(25)=\delta_{c,3PB}(t)\ :\ \delta_{c,3PB}(25) \tag{3}$$

Thickness effect on the critical CTOD is approximated as Eq.(4)

$$\delta_{c,3PB}(t)=\delta_{c,3PB}(25)\times\left(\frac{25}{t}\right)^{1/2} \tag{4}$$

Then, the conversion equation of the $\beta(t)$ for a given plate thickness t from the $\beta(25)$ under the constant a/t was formulated as Eq.(5).

$$\beta(t)=\beta(25)\times\left(\frac{25}{t}\right)^{1/2} \tag{5}$$

The applicability of this conversion equation to the CSCP and ESCP was demonstrated as shown in Figs. 8 and 9, where the $\beta(12.5)$ and $\beta(50)$ predicted from $\beta(25)$ by using Eq.(5) were in good agreement with the FE-analytical results. This implies that the $\beta(t)$ for CSCP and ESCP with a given plate thickness t can be estimated without FE-analysis if only the $\beta(25)$ is given for a various crack depth ratio a/t.

4. Conclusion

Crack-tip plastic constraint in beam-to-column connections with a surface crack 1) at the bottom of a conventional type of weld access hole and 2) at weld start/end points of butt welds to connect beam flange and diaphragm subjected to bending moment were analyzed by FEM. The equivalent CTOD ratio β used for engineering toughness correction for constraint loss for the beam-to-column connections was found to be represented by those for the wide plate components with the same size of a crack subjected to tension load. Then, the β was systematically estimated by means of the wide plate component under tension load. From these analyses, the crack depth effect on β for CSCP and ESCP could be quasi-theoretically formulated as the plate thickness effect under a given crack depth ratio a/t.

References

ISO 27306-2009(E): Metallic materials—method of constraint loss correction of CTOD fracture toughness for fracture assessment of steel components.

ISO 12135: 2002(E), Metallic materials – Unified method of test of the determination of quasistatic fracture toughness.

Beremin, F., 1983, A local criterion for cleavage fracture of a nuclear pressure vessel, Metall. Trans. A, 14a, 2277–2287.

Harrison, J.D., 1980, The State-of-the-Art in Crack Tip Opening Displacement (CTOD) Testing and Analysis, Part 1 – Background and Testing Methods Metal Construction, 12, 415-422.

Minami, F., Brückner-Foit, A., Munz, A. and Trolldenier, B., 1992, Estimation procedure for the Weibull parameter used in the Local Approach, Int. Journal of Fracture, 54, 197-210.

Minami, F., Ohata, M., Shimanuki, H., Handa, T., Igi, S., Kurihara, M., Kawabata, T., Yamashita, Y., Tagawa, T., Hagihara, Y., 2006, Method of constraint loss correction of CTOD fracture toughness for fracture assessment of steel components, Eng. Fract. Mech., 73, 1996–2020.

Ohata, M. and Minami, F., 2012, Equivalent CTOD Ratio β for Engineering Assessment of CTOD Correction for Constraint Loss, ASME Journals, J. Pressure Vessel Technology, 134(5), 051403.

Ruggieri, C., Minami, F., Toyoda, M., Hagihara, Y., Inoue, T., 1992, Local Approach to Notch Depth Dependence of CTOD Results, Journal of the Society of Naval Architects of Japan, 171, 493-499

Toyoda, M., 1995. How Structures Fared in Japan's Great Earthquake. Welding Journal 74, 31-42.